A modeling study of climate change impacts on recharge and surface-groundwater interactions for the Thomas Brook catchment (Annapolis Valley, Nova Scotia)

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ABSTRACT
Groundwater-surface water interactions impact aquifer recharge and groundwater levels, and are in turn affected by direct and indirect anthropogenic factors, including pumping and climate change. In the present study, a coupled numerical model was implemented for a small (8 km^2) catchment in Nova Scotia to investigate how the hydrological response is affected by climatic changes. The model was calibrated for the year 2005 based on streamflow and groundwater data. The Canadian Regional Climate Model (CRCM4) was then used to generate 30-year climate forecasts. The simulation outputs were statistically analyzed using a non-parametric test to detect trends.

RÉSUMÉ
Les interactions entre l'eau de surface et l'eau souterraine ont un impact sur la recharge et le niveau des nappes, et sont à leur tour influencées par des facteurs anthropiques directs et indirects tels que le pompage et les changements climatiques. Dans cette étude, un modèle numérique couplé a été développé pour un petit bassin (8 km^2) de la Nouvelle-Écosse afin d'étudier la réponse du système aux changements climatiques. Le modèle a été calibré pour l'année 2005, basé sur des données hydrauliques et hydrogéologiques. Le modèle de climat régional canadien (MCRC4) a été utilisé pour générer des prévisions météorologiques sur 30 ans. Les résultats des simulations ont été analysés en utilisant un test non-paramétrique pour détecter les tendances.

1 INTRODUCTION

The objectives of the study were to investigate the hydraulic connection between surface water and groundwater using modeling and the impact of climate change on a small-scale catchment (Thomas Brook, 8 km^2) of the Annapolis Valley, an important agricultural region in Nova Scotia. More than 90% of the Valley's population, and 100% of the Thomas Brook catchment residents, now rely on groundwater for their water supply, owing mainly to limited surface water and increasing surface water contamination. This catchment was considered representative of the Valley in its geology, topography, and land use (Gauthier, 2008). About half of the territory of the catchment is harvested, serves as pasture, or corresponds to orchards. Variable levels of nitrates were found in bedrock wells (see Trépanier, 2008), an indication of the importance of groundwater/surface water interactions and of spatial variability in catchment processes.

Physically-based models that feature some form of coupling between the governing equations of surface flow and subsurface flow (unsaturated and saturated zones) are increasingly used in integrated water resources and environmental studies. Numerical models based on the fully three-dimensional Richards equation for variably saturated subsurface flow and on one- or two-dimensional approximations to the Saint-Venant equations for surface flow (e.g., Bixio et al., 2000; VanderKwaak and Loague, 2001; Kollet and Maxwell, 2006; Jones et al., 2008) are starting to be used on natural catchments with complex geometries.

Recent studies (Rivard et al., 2003; Rivard et al., 2008b) have identified both upward and downward trends in baseflow and groundwater level time series in eastern Canada, depending on the location and series length. Since statistical tests depend heavily on the series length, and most areas do not have data records beyond 30 years, modeling represents a valuable tool to predict changes in recharge and groundwater levels. Recent studies were conducted in different areas of Canada using atmospheric forcing obtained from climate models as input to hydrogeological models (e.g. Jyrkama and Sykes, 2007; Scibek et al., 2007; Valeo et al., 2007). This paper describes the realization of a 30-year simulation with a coupled physically-based hydrological model using daily forcing from 2041-2070 climate forecasts generated by the Canadian Regional Climate Model (CRCM4) with emissions scenario A2.

2 DESCRIPTION OF THE STUDY AREA

2.1 Physiography and climate

The Thomas Brook (TB) catchment is located within the Annapolis Valley in Nova Scotia. The Valley is located in the eastern portion of the Appalachian physiographic region, which extends from Newfoundland (Canada) to Alabama (USA). It is sited along the Bay of Fundy, between the North and South Mountains, and is included within Kings and Annapolis Counties (see Figure 1). It is approximately 100 km long and 10 to 15 km wide; it encompasses approximately 2100 km^2 and includes five watersheds, of which the Annapolis and Cornwallis are the largest.

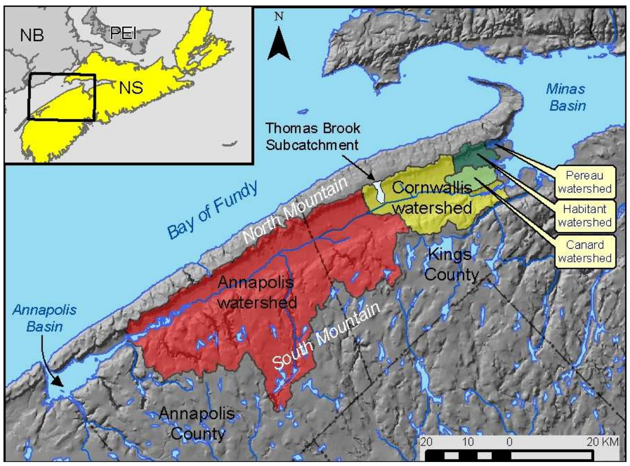

Figure 1: Location of the Thomas Brook catchment within the Annapolis Valley, NS

The TB catchment is located in the north-western part of the Cornwallis watershed (see Figure 1) and covers approximately 8 km^2. About two-thirds of the study area is relatively flat, whereas the northern part is very steep and includes the North Mountain cuesta, where the elevation changes from 220 to 70 m over about 1.5 km. A discharge zone with numerous springs is located at the foot of this abrupt slope. These springs are commonly used as water supply sources by the Valley residents.

The moderating effect of the ocean and the climatic protection provided by the North and South Mountains allow the Annapolis Valley to have the warmest temperatures and the second lowest annual precipitation totals in Nova Scotia (Rivard et al., 2008a). The Kentville weather station, located 20 km south-east of the TB catchment, provides a 30-year mean for total precipitation of 1211 mm/y, of which 948 mm fall as rain. The region is characterized by two major periods of precipitation: in the spring and in the fall. Evapotranspiration was estimated to be 689 mm using the Penman-Monteith equation specifically for year 2005 (see Gauthier, 2008).

2.2 Geological context

Figure 2 illustrates the bedrock geology of the Annapolis Valley. The TB catchment, located in the northern part of the Valley, includes three geological formations that belong to the Triassic-Jurassic Fundy Group (Mesozoic rocks). The Fundy Group rocks have a stratigraphic thickness varying between 2 and 10 km (increasing northward). The strata dip to the north at ~4-12^{o}. The study area comprises, in ascending order: the Wolfville, Blomidon, and North Mountain formations.

The Wolfville Formation, which underlies most of the Valley floor, is comprised of medium- to coarse-grained sandstone, with subordinate pebbly and conglomeratic beds whose clasts are derived from the adjacent metamorphic and granitic highlands, as well as shale and siltstone strata. Near the surface, the sandstones and conglomerates are poorly cemented. The Blomidon Formation comprises the same lithologic types as the Wolfville Formation, but finer grained beds are usually reported to be more abundant. The North Mountain

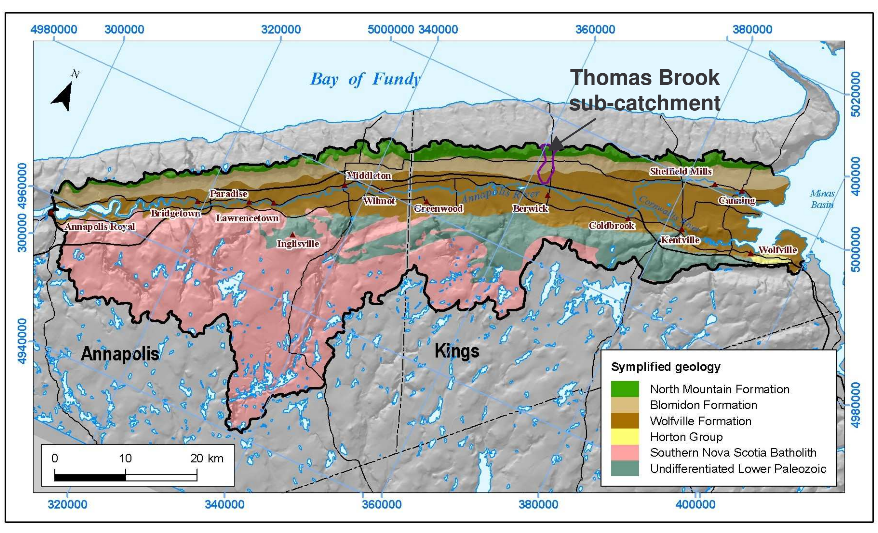

Figure 2: Bedrock geology of the Annapolis Valley (taken from Rivard et al., 2008a)

Formation consists of a series of massive and amygdaloidal basalt flows with well-developed columnar jointing.

The Quaternary sediments in the TB catchment consist mostly of tills, but glaciolacustrine clays with underlying glaciofluvial sands and gravels are present in the southern part (Figure 3). Till composition is the result of four different ice flow phases and is also related to the underlying bedrock lithology. Deposits are thinner in the upland areas and thicker in the valley (up to 10 m). Surficial deposits in this catchment are therefore not good aquifers, even when sand is present, due to the limited (or inexistent) saturated thickness.

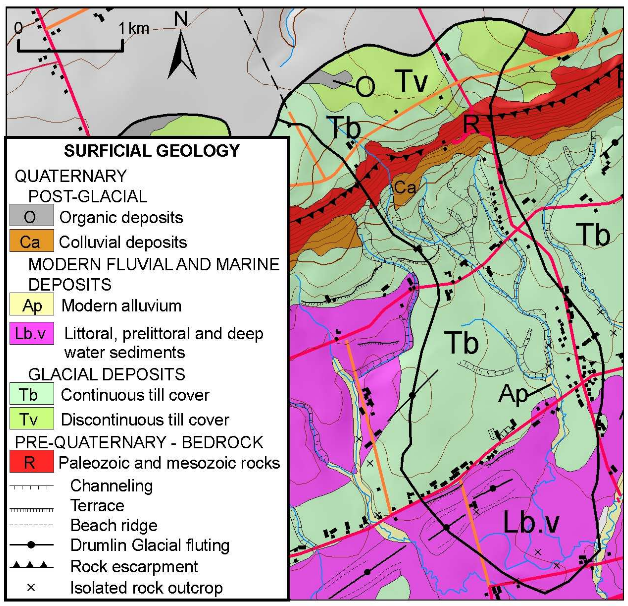

Figure 3: Surficial geology of the Thomas Brook catchment (taken from Gauthier, 2008).

2.3 Hydrogeological context

As a result of extensive variations in lithologies, bed thickness, and fracturing, the hydrogeological properties within each formation appear to be quite heterogeneous. Field measurements indicate that movement of groundwater is predominantly controlled by fractures/ bedding planes, although sandstones of the Wolfville Formation likely have significant primary porosity (28% on average, compared to 8% for the Blomidon Formation). However, pumping tests from the provincial database showed that pumping wells generally behave similarly to porous media, with drawdown following a Theis-type curve (Rivard et al., 2008a).

Aquifers of these formations are often confined. Nevertheless, groundwater is topography-driven: groundwater flows from the topographic highs of the North Mountain towards the Cornwallis River in the centre (lower part) of the Valley floor. Groundwater levels are generally shallow, having a median depth of 6.3 m. Characterization of till deposits was conducted using a Guelph permeameter.

Preferential groundwater recharge occurs through vertical fractures of the North Mountain basalts and on flat surfaces (i.e. in the Valley) where sediments are sandier. The mean recharge rate was estimated to range between 306 and 347 mm/y based on hydrograph separation (Gauthier, 2008), 1-D vertical simulations of flow (Trépanier, 2008) and the water balance method.

3 NUMERICAL MODEL

The CATHY (CATchment HYdrology) numerical model was used to estimate overland flow, aquifer recharge, groundwater levels, and local hydraulic exchanges in the TB catchment. The model couples a subsurface module representing three-dimensional unsaturated and saturated zone flow with a surface module simulating one-dimensional overland and channel flow (Bixio et al., 2000).

For the implementation of the numerical model for the TB catchment, a geological model was created in gOcad for both bedrock and surficial deposits. Topographic data were read in from a digital elevation model (DEM) based on the National Topographical Data Base at a 1:50,000 scale (http://www.ctis.nrcan.gc.ca/) to determine the surface flow directions and drainage areas, and to define the overland flow and stream channel cells. The 3D subsurface grid was generated by CATHY. The attribution of material properties to each zone was performed using the goCad and ArcGIS software packages. The setup of the model for the TB study area is described in Gauthier (2008).

Precipitation minus evapotranspiration on a daily basis for year 2005 was provided as input for the atmospheric fluxes to the model. This year was selected because it had the most complete streamflow record available for the Thomas Brook. Values came from the Kentville station (Environment Canada website). Hydraulic conductivity (K), specific storage, and porosity values, either based on results from fieldwork, provincial databases, or the literature, were assigned to each geological unit. Parameters for the unsaturated zone (such as soil water retention functions) and surface routing parameters (Gauckler-Strickler roughness and Leopold-Maddock geometric scaling coefficients) were assigned representative values taken from the literature. Boundary conditions were no-flow along the lateral boundaries and the base of the catchment and atmospheric fluxes at the surface. Initial conditions were obtained by simulating the drainage of the catchment starting from fully saturated conditions and with zero atmospheric forcing.

The model contains 17 layers and seven different geological units (Figure 4). The surface mesh for the catchment area contains 2,234 cells. Each layer, except the bottom-most one, is parallel to the surface and has a constant thickness. The thinnest layers (0.1 m) were those closest to the surface, in order to accurately resolve rainfall-runoff-infiltration partitioning and in general to better capture the interactions between surface water and groundwater. The layers were progressively coarsened with depth, to a maximum thickness of 10 m for layers 15 and 16. A thickness ranging from 10 m (south end of the catchment) to 200 m (north end) was assigned to the bottom-most layer 17. Assigned values are presented in Figure 4 and Table 1.

In the model, the accumulated snow was transformed into rain (i.e. available water for infiltration and runoff) whenever the maximum daily land surface temperature rose above zero. For the 2005 dataset used, this pre-treatment of the meteorological data resulted in six infiltration events over the winter. This is reasonably representative of the mild winter characteristics of the Annapolis Valley micro-climate.

Model calibration was performed using streamflow data from the Thomas Brook station at the outlet and two monitoring wells with data for the year 2005, as well as groundwater levels in 30 locations (visited wells) and the mean recharge rate previously estimated. The average annual simulated flow was very close to the observed discharge at the Thomas Brook outlet (0.18 versus 0.17 m^3/s). The modeled and observed water table levels for the two monitoring wells respond in a similar way to rainfall pulses and to the extended drier period in the summer, although the model's response to the atmospheric input is more pronounced. Discrepancies over time range between 0 and 2 m, well within the DEM accuracy (i.e. ≈5 m).

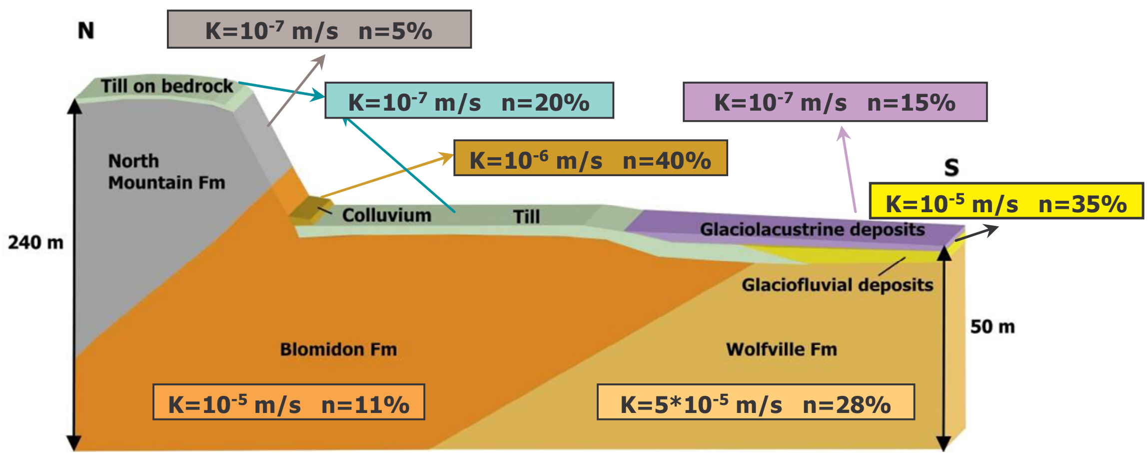

Figure 4: Conceptual model used in CATHY (not to scale). Vertical cross section along a north-south transect. K is saturated hydraulic conductivity and n is porosity.

Table 1: Hydraulic parameters used in the model

Geological unit	Hydraulic conductivity (m/s)	Porosity (%)	Specific storage (m^{-1})
North Mountain	1×10^{-7}	5%	1×10^{-5}
Blomidon	1×10^{-5}	11%	1×10^{-5}
Wolfville	5×10^{-5}	28%	1×10^{-4}
Till	1×10^{-7}	20%	1×10^{-3}
Glacio-lacustrine deposits	1×10^{-7}	15%	1×10^{-3}
Glacio-fluvial deposits	1×10^{-5}	35%	1×10^{-2}
Colluvium	1×10^{-6}	40%	0.1

The match in groundwater levels for the year 2005 is also good. A coefficient of determination (R^2) of 0.994, a mean error of 0.33 m, a mean absolute error of 3.7 m, and a root mean square error of 5.5 m were obtained (Gauthier, 2008). Finally, the simulated recharge for 2005 was found to be 349 mm/y, close to the upper limit estimated with other methods.

The average return flow, which is the part of overland flow that comes directly from the subsurface (groundwater that returns to the surface), is 0.10 m^3/s. The ratios found between return flow and overland flow are quite high (around 50%), reflecting the influence of topography, especially along the cuesta where numerous springs generate most of the return flow. The simulation also showed that recharge rates were highest at the foot of the North Mountain, mainly due to the presence of the permeable colluviums. As expected, varying the porosity and specific storage parameter values had much less impact on the catchment response than changing K.

4 30-YEAR CLIMATE CHANGE SCENARIOS

The impacts on streamflow, aquifer recharge, and other hydrologic components of the TB catchment of 30-year climate forecasts from the CRCM4-A2 were analyzed with the CATHY model. The CRCM4 uses results from the Third Generation Coupled Global Climate Model (CGCM3) with a 45x45 km^2 mesh (112 x 88 grid points). Daily atmospheric forcing from CRCM4 for the 1961-1990 reference period was also used to generate 30-year series for comparison to observed data.

Daily data provided by CRCM4 are: total precipitation, ET, maximum and minimum temperatures, snow cover, and total runoff. The snow cover represents the water equivalent of accumulated snow on the land surface; therefore, this variable is expressed in mm per day rather than per year. Total runoff represents the drainage of larger basins considered by the CRCM and can be rescaled and compared to the outlet streamflow of the Thomas Brook. 30-year periods were selected in order to obtain a statistically significant representation of climate variations and catchment hydrodynamic responses for past and future periods.

4.1 Statistical analysis of 30-year climate forecasts

First, climate data for the reference period obtained from the CRCM4 were compared to observed data from the Kentville station to quantify the bias resulting from the model. Secondly, future data were compared to past CRCM4 data to examine the impact of CO_2 doubling on the various simulated variables. Because the TB catchment is located at the meeting point of four CRCM tiles, an arithmetic mean of the simulated values over these four tiles was used. The variables are presented for each time period individually.

Reference (past) period (1961-1990)

Results from the comparison between observed and simulated data are summarized in Table 2. CRCM4 underestimates minimum temperature (bias of 3.6ºC/y), but simulates well the maximum temperature (bias of 0.3ºC/y). Total precipitation is also underestimated by CRCM4 simulations (bias of 8.7%) and annual values appear to be less pronounced than observations (not shown). The simulated evapotranspiration (ET) was compared to three methods of estimation: Thorthwaite (Chow, 1968), Coutagne (1954), and Turc (1955). The first method refers to potential ET, whereas the last two are gross estimates of actual ET. The CRCM4 ET is between potential and real ET values, but closer to actual ET values, with an overestimation of less than 7% for both methods.

Table 2 : Summary of comparison between CRCM4 simulated data and observed data from the Kentville station

Climate variable	**CRCM4** (over 30 years)	**Observed** (over 30 years)	**Absolute bias**	**Relative bias**
Total precipitation (mm/y)	1106	1211	-105	-8.7%
Evapotranspiration (mm/y)	472	455 (Turc, 1955)	17	3.7%
Snow cover (mm/d)	29.9	59.9	-30	-50.1%
Min temperature (ºC/y)	-1.5	2.2	-3.6	-
Max temperature (ºC/y)	11.8	11.5	0.3	-
Total runoff (mm/y)	637	661 (year 2005, TB outlet)	24	3.6%

Although the climate is colder (with underestimated Tmin and a relatively correct Tmax), CRCM4 simulates 50% less snow cover than what was observed at the Kentville station. This might be due to the underestimation in total precipitation (-8.7%) combined to the overestimation of ET, but also to the location of the weather station (since there is probably much less wind to blow the snow away in the center of the valley, protected by the Mountains). Total runoff is relatively well represented with a difference of only 3.6% with the 2005 measured values.

Mean monthly data were also examined to see if biases observed for annual values were representative throughout the year. Differences in temperature (both min and max) appeared to be quite constant throughout the year. However, total precipitation appeared to be overestimated during warmer months (from May to August) and underestimated during the colder period (from October to March) up to 30 mm, thereby providing a partial explanation for the snow cover underestimation.

Future period (2040-2070)

As expected, the climate scenario for the future period predicts that minimum and maximum temperatures, as well as ET, will increase (see Table 3). Total precipitation is surprisingly similar to that of the reference period, but the standard error on year to year precipitation is larger for the reference period (128 mm versus 102 mm), suggesting more inter-annual variability. The CRCM4 simulation, which had largely underestimated the snow cover for the reference period, predicts 54% less snow cover for the future period compared to the simulated reference period. This could reduce significantly the major spring recharge event during the snowmelt period. However, warmer temperatures will induce winter precipitation to fall more frequently as rain and will provide winter runoff to the streams and recharge to the aquifer and throughout the year. The future mean value of total runoff is similar to the value simulated for the reference period, mainly because total precipitation does not change significantly.

Mann-Kendall trend results

The commonly used non-parametric Mann-Kendall test along with the TFPW process to eliminate cross-correlation (see Rivard et al., 2008b) were utilized to estimate upward and downward trends for annual values of the parameters generated by the CRCM4. Table 4 shows that only four variables of the future period exhibit statistically significant trends at the 10% level, with especially strong magnitudes for temperature. The Sen's slope is a ranked-based robust estimate of the slope that corresponds to the mean variation over one year. Therefore, a 0.087℃ variation for the minimum temperature represents a 2.6℃ increase over 30 years, which is considerable. A summary of the means and standard errors (μ±σ) is also presented in Table 4. Total precipitation appears to be stable for both historical and future series. Predictions for ET show a variation of +12% (slope*30/μ) for the future period. Trends are probably present in the future period because climate change (CO_2 increase) gives rise to a combined effect (e.g., the increase of temperature will increase ET) that could accelerate changes in parameter values.

Table 3: CRCM4 values for the reference and future periods

Climate variable	Past (over 30 years)	Future (over 30 years)	Absolute difference	Relative difference
Total precipitation (mm/y)	1106	1161	55	5%
Evapotranspiration (mm/y)	472	549	77	16%
Snow cover (mm/d)	29.9	14	-16	54%
Min temperature (ºC/y)	-1.5	1.8	3.3	-
Max temperature (ºC/y)	11.8	14.5	2.7	-
Total runoff (mm/y)	637	611	-26	-4%

Table 4: Results of the Mann-Kendall test for historical and future series of annual values

Parameter	Observed data for the past period 1961-1990		Simulated data over the future period 2040-2070	
	μ ± σ *	Sen's slope	μ±σ *	Sen's slope
Total precipitation (mm/y)	1200 ± 173	NS**	1161 ± 128	NS**
Evapotranspiration (mm/y)	455 ± 21	NS**	549 ± 30	2.274
Snow cover (mm/d)	60 ± 38	NS**	14 ± 9	-0.332
Min temperature (ºC/y)	2.2 ± 0.6	NS**	1.8 ± 1.0	0.087
Max temperature (ºC/y)	11.5 ± 0.6	NS**	14.4 ± 0.8	0.073
Total runoff (mm/y)	-	-	611 ± 118	NS**

* μ±σ: mean plus or minus standard error ** NS: non-significant trend

4.2 Simulations with CATHY

For the two 30-year CATHY model simulations (1961-1990 and 2041-2070), for which a daily output was generated, mean annual and seasonal values for streamflow, recharge, and groundwater depth have been compared. The atmospheric fluxes (precipitation minus evapotraspiration) used in CATHY were 634 mm/y for the reference period and 612 mm/y for the future period, showing only a 4% decrease (despite the 16% increase in ET and 5% in precipitation). This is likely due to the distribution of values during the year.

Results for total runoff (corresponding to the outlet Thomas Brook streamflow) and aquifer recharge are presented on an annual basis in Figure 5 for the reference period. The annual atmospheric fluxes have been added for comparison. It can be observed that the curves behave in a relatively similar manner. The streamflow curve, however, shows less pronounced minimum and maximum values than that of the atmospheric flux, as expected for a catchment-integrated process. Recharge appears to be more stable and remains relatively high even during low input periods. The mean aquifer recharge is 360 mm/y and the mean streamflow is 0.158 m^3/s (i.e. 621 mm/y). Similar results were obtained for the future period.

Thomas Brook streamflow

Past and future simulations for the Thomas Brook streamflow show similar values for both annual and seasonal values (Figure 6), mainly due to similar predicted precipitation. The slight increase in ET is not sufficiently important to result in a large streamflow decrease.

The application of the Mann-Kendall test showed that only the summer values for the future period had a significant trend at the 10% level, with a value of -0.0024 m^3/s. This is equivalent to a decrease of 0.07 m^3/s over 30 years; since the mean summer value is 0.093 m^3/s, this decrease is considerable.

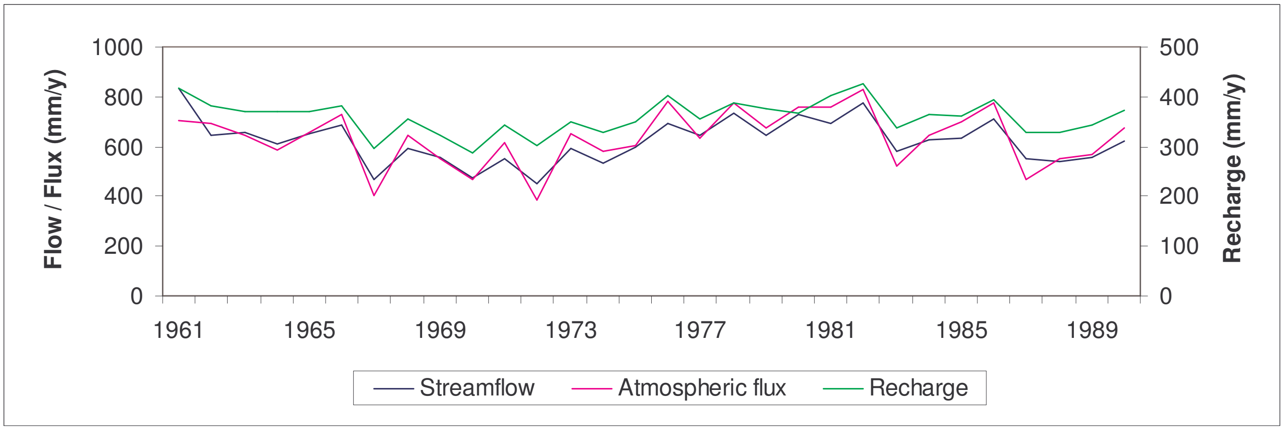

Figure 5 : Mean annual streamflow, aquifer recharge, and atmospheric flux values for the reference period (1961-1990)

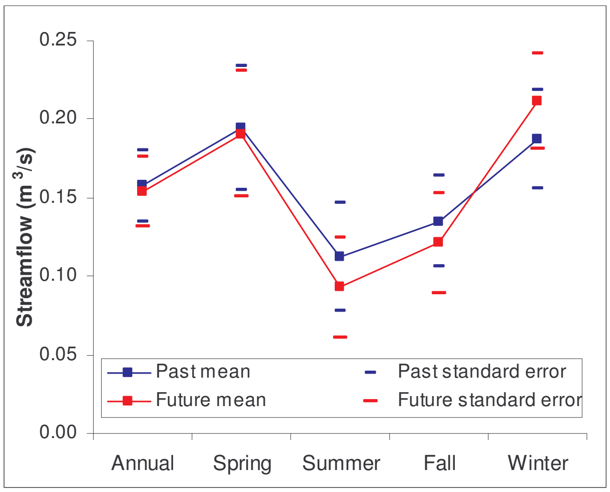

Figure 6 : Mean and standard error for annual and seasonal simulated streamflow values

Aquifer recharge

The recharge does not seem to be affected by the increase in temperature and evapotranspiration and decrease of the snow cover in the spring period. Figure 7 shows that past and future values are very similar throughout the year. This is likely due to the fact that snow precipitation is replaced by the same amount of rain. Once again, the only variable showing a (modest) statistical trend was the summer recharge, with a decreasing trend of -0.504 mm/y (i.e. 15 mm over 30 years), which is relatively small.

Groundwater levels

In addition to mean values obtained for the entire catchment, groundwater levels were calculated at three sites (corresponding to visited sites), each located in a different geological formation (not shown). The groundwater depth is usually quite close to the surface, especially in the Blomidon Formation well. In the Wolfville Formation, values average 6.5 m. For comparison, measurements (from fieldwork and databases) vary from 0 to 30 m below the surface, with the largest variations observed in the North Mountain basalts; the median is 6.3 m.

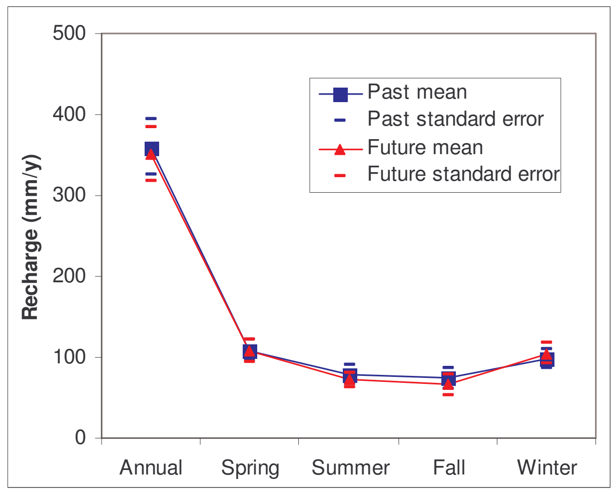

Figure 7: Mean and standard error for annual and seasonal simulated recharge values

The model predicts that groundwater levels for the future period will be slightly lower during most of the year, but higher during the winter, due again to the milder conditions and more frequent rain precipitation instead of snow. The well located in the North Mountain Formation showed a noticeable decrease in its water level of approximately 1 m. This could be due to the fact that this formation is poorly protected by the thin till cover against ET.

5. CONCLUSION

A modeling study of a small subcatchment (8 km^2) in the Annapolis Valley, Nova Scotia, was conducted to investigate groundwater–-surface water interactions under climate change. The coupled model was first validated using observed or previously estimated values of groundwater levels, aquifer recharge, and streamflow data for the year 2005.

Simulation results based on 30-year CRCM4 climate forecasts and the validated coupled model showed that groundwater resources in the Thomas Brook catchment should not be affected significantly by climate change. Total runoff and aquifer recharge for the future period (2041-2070) are similar to those of the reference period (1961-1990) and few parameters showed a statistically significant trend. However, more analysis needs to be performed to investigate in detail water exchanges and different ratios such as infiltration / recharge and return flow / overland flow. Furthermore, additional simulations using other climate models should be performed to reduce uncertainty.

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